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A Study on the Visual Impact of Photovoltaic Facilities on Rural Landscapes With the Visual Q-Method

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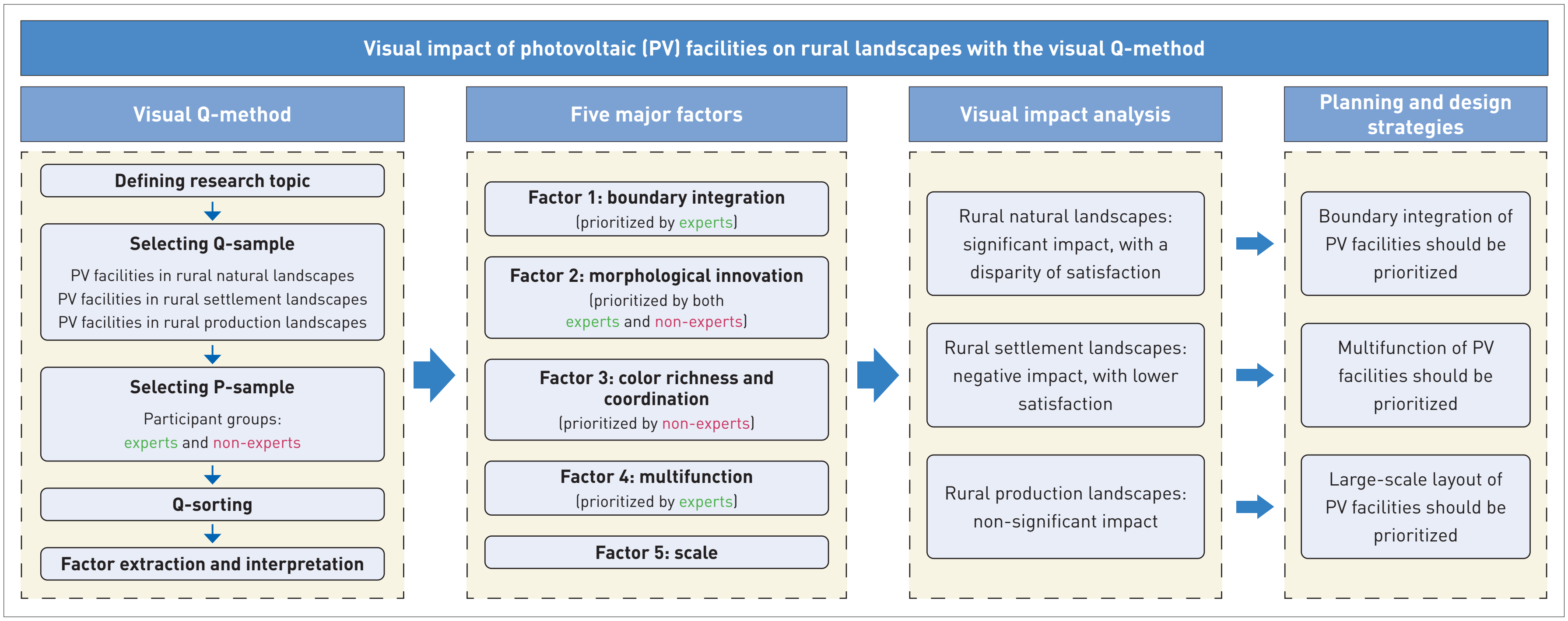
GRAPHICAL ABSTRACT



ABSTRACT

The abundant land resources in rural areas have allowed for a rapid growth of the photovoltaic (PV) industry. However, the large-scale construction of PV facilities has significantly impacted rural landscapes. This study systematically analyzed the visual impact of PV facilities on rural landscapes using the visual Q-method. By selecting images of PV facilities within rural natural, settlement, and production landscapes from different regions in China, visual perception scoring was conducted between experts and non-experts. Statistical analysis of the scoring results using PQMethod2.35 software identified five primary factors influencing the visual impact of PV facilities on rural landscapes: boundary integration, morphological innovation, color richness and coordination, multifunction, and scale. The findings indicate that PV facilities exert the most significant visual impact on rural natural landscapes, with a clear disparity in satisfaction. PV facilities negatively affect rural settlement landscapes, with dissatisfaction frequencies significantly exceeding satisfaction frequencies. However, their visual impact on rural production landscapes is negligible. The results will provide a reference for landscape planning and design of PV facilities in rural areas, supporting the sustainable development of PV facilities.

KEYWORDS

Visual Q-method; Rural Landscape; Photovoltaic Facility; Photovoltaic Landscape; Visual Impact

HIGHLIGHTS

- Boundary, morphology, color, multifunction, and scale of PV facilities are key aspects
- PV facilities significantly impact natural landscapes with polarized ratings; boundary integration is emphasized
- PV facilities have a negative impact on rural settlement landscapes; multifunction is accentuated
- PV facilities have a non-significant impact on rural production landscapes; large-scale layout is prioritized

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1 Introduction

The escalating severity of climate change has prompted the global consensus on reducing greenhouse gas emissions, making the reduction of fossil fuel usage and the shift toward clean energy an inevitable trend in global energy development[1]. As an efficient and feasible approach to solar energy utilization[2], photovoltaic (PV) systems have been witnessed a rapid development in recent years under policy guidance worldwide[3]. According to data from the European Commission, global installed PV capacity reached 1,608 GWp from 2010 to 2023, with China contributing approximately 671 GWp (42% of the global total)[4]. With the growth of rural economies and the improvement of living standards, rural areas are becoming the primary source of future electricity additions and major regions for electricity demand in China. Surveys indicate that the total installable capacity of rooftop PV in rural China is 197 million kW, demonstrating vast development potential[5]. Meanwhile, various “PV plus” production models in rural areas, such as agro-PV, fishery-PV, pastoral-PV, and forestry-PV ones, have significantly enhanced the comprehensive utilization of rural resources[6][7].

Compared with urban areas, rural regions typically possess natural ecological environments that are more subject to the potential impacts of PV facilities. Although PV energy offers significant environmental advantages over traditional fossil fuels, large-scale PV facilities may lead to issues such as extensive land occupation, changes of rural landscapes, and local ecological impacts, which have gradually attracted widespread societal concerns[8]. Countries and regions such as the Netherlands[8] and Canada[9] have promoted the construction of large-scale renewable energy infrastructure, but the caused visual intrusion has triggered strong public opposition. Against this backdrop, scholars have proposed many methods to assess the visual impact of large-scale renewable energy infrastructure[10]~[12], and evaluation approaches initially developed for wind power infrastructure have been adapted to studies on large-scale ground-mounted PV systems[13]. Researchers have proposed quantitative indicators and calculation methods for visual impact based on visibility, color, fractality, and concurrency. For example, Chiabrando Roberto et al. used OAI_{SPP}, a visual impact assessment tool, to measure the visual impact of PV plants on landscapes[14].

In early studies on PV facility visual assessment, most research was conducted under the assumption that their visual impacts were inherently negative and required mitigation, and that PV facilities must be concealed. There was little discussion on how to actively integrate PV facilities into the landscape. In 2016, Alessandra Scognamiglio et al. introduced the concept of “photovoltaic landscapes” through inclusive design methods[2], integrating PV systems as part of landscape design to reduce their visual impacts. In 2021, Dirk Oudes et al. proposed the idea of “solar landscape” which a spatial arrangement combining solar power plants and landscapes[15]; in 2022, they further established a conceptual framework of “solar energy landscape” covering sustainable technology, economy, environment, and social aspects[16].

Since 2003, Chinese scholars have begun exploring the integration of PV systems with the landscape[17]. Research primarily aimed at promoting PV facilities, with topics covering the integrated design of PV systems with landscape elements[18], the application of digital PV technology in rural landscape facilities[19], planning and development modes for PV towns[20], and construction modes for PV eco-agricultural leisure parks[21]. Currently, national policies have made clear requirements for PV system site selection, mandating avoidance of cultivated land, ecological protection red lines, historical and cultural conservation zones, and natural forests and water bodies[22][23]. However, systematic research on the visual impact of PV facilities on rural landscapes remains scarce, and relevant regulatory details are incomplete, resulting in a lack of specific landscape coordination guidelines for practice. This poses challenges for rural areas to balance renewable energy development with landscape protection when promoting PV facilities. There is an urgent need for scientific assessment of the visual impact of PV facilities on rural landscapes so as to inform policy formulation.

The visual Q-method, as a research approach combining subjective perception and quantitative analysis, sees efficient and intuitive advantages in the field of landscape evaluation and planning. This method was first applied to landscape evaluation and planning by Ervin H. Zube et al. and has further been adopted into diverse research contexts[24]. For example, Simon Swaffield and John R. Fairweather used the visual Q-method with landscape photographs to investigate tourists' attitudes toward the effects of land use changes in New Zealand[25]; they also employed the visual Q-method to explore differences in visitor experiences with landscape photographs[26], demonstrating the method's effectiveness in tourism experience research; Andra Ioana Milcu et al. used the visual Q-method to explore diverse landscape preferences and potential conflicts among residents in rural Romania[27]. Regarding visual impacts of PV facilities, Simona Naspetti et al. collected landscape images of various PV plants in Italian urban and rural environments and used the visual Q-method to explore their impact on local landscapes and land use[24]; Ming Lu et al. applied the Q-method to investigate the impacts of PV systems on urban landscapes across different land-use types[28]. Based on the aforementioned studies, this study employs the visual Q-method to systematically assess the visual impact of PV facilities on rural landscapes in China, providing a scientific basis for the sustainable development of PV infrastructure in rural areas.

2 Methodology and Data Collection

2.1 Overview of the Q-Method

British psychologist William Stephenson first proposed "Q-Methodology" (Q-method hereafter) in the 1930s and elaborated on it in his 1952 article *Q-Methodology and the Projective Techniques*[29]. The Q-method is a research approach combining quantitative and qualitative methodologies. Differing from traditional statistical methods that rely on large-size random samples, the Q-method emphasizes intensive testing on a small number of participants or deriving extensive feedback from participants[30]. Since the 1980s, Q-method research has expanded from psychology to disciplines such as health sciences, nursing, policy science, public administration, and environmental economics[30].

A Q-method study typically involves five steps[31]. 1) Defining research topic; 2) selecting Q-sample: the Q-sample should comprehensively cover all possible perspectives on the research topic; 3) selecting P-sample (i.e., participants): the chosen participants should be able to provide insightful or critical views on the research topic, and their composition and quantity should be determined by specific needs; 4) Q-sorting: assisting participants in understanding research objectives and completing the sorting of the Q-sample; and 5) factor extraction and interpretation: inputting participants' scores into statistical software and interpreting the analysis results.

The Q-method serves as a bridge between human perception and the environment[28]. It should be noted that Q-samples may include not only textual materials but also ensembles of expression forms such as paintings, artworks, images, music, and videos[32]. While textual Q-samples remain the most common form in current research, other forms offer their advantages. For example, the one uses visual stimuli as Q-samples is termed "visual Q-method"[33]: using images as Q-samples provides participants with more intuitive, authentic scenarios, enabling them to recall associated emotions, memories, and thoughts that may be difficult to articulate verbally, thereby enhancing the reliability of interviews.

2.2 Research Design

2.2.1 Defining Research Topic

Based on the research objectives, the research topic of this study is employing the visual Q-method to investigate the visual impact of PV facilities on rural landscapes.

2.2.2 Selecting Q-Sample

In this study, photographs reflecting PV facilities and the surrounding environments were selected as Q-samples. The selection of Q-samples was determined by two aspects: the rural landscape typology[34] and the application forms of PV facilities[24]. Rural landscapes can be classified into natural landscapes, settlement landscapes, and production landscapes[34]. Natural landscapes encompass rivers, vegetation, mountains, and nature reserves within rural areas. Settlement landscapes refer to architectural spaces closely related to human habitation. Production landscapes refer to the landscapes integrating labor activities and outcomes, including agricultural, forestry, and pastoral landscapes[34][35]. Application forms of PV facilities can be categorized as integrated installations and standalone installations[24]. In rural areas, integrated PV installations are typically attached to or embedded within rural structures (e.g., rooftops, facades). Standalone PV installations often appear as separate PV panels or sculptural installations[36]. Images of rural PV landscapes across China were collected and filtered by removing duplicates or unrepresentative examples[24], resulting in 36 finalized Q-samples which covers six categories: integrated PV installations in natural landscapes, Images 1 ~ 6; standalone PV installations in natural landscapes, Images 7 ~ 12; integrated PV installations in settlement landscapes, Images 13 ~ 18; standalone PV installations in settlement landscapes, Images 19 ~ 24; integrated PV installations in production landscapes, Images 25 ~ 30; and standalone PV installations in production landscapes, Images 31 ~ 36.

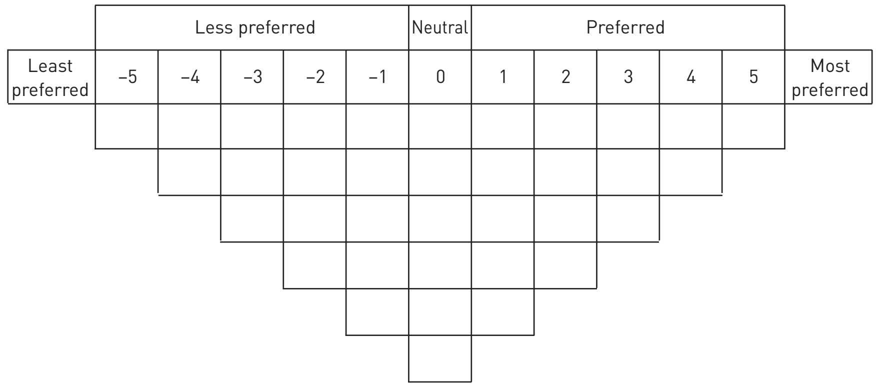
2.2.3 Selecting P-Sample

To ensure diversity in views, two groups of participants were recruited: experts (with knowledge about PV facilities and rural landscapes) and non-experts. The expert group comprised landscape architects, architects, planners, and PV engineers, while the non-expert group included villagers, rural tourists, and other interested individuals who were interested in this study.

Q-method does not specify strict requirements for P-sample size. Generally, the number of participants is less than Q-samples[37]. However, considering potential invalid responses, the initial P-sample pool was expanded in this study. Besides, given experts' influence on rural PV policies[24], the expert group (24 participants) slightly outnumbered the non-expert group (17 participants). Data were collected through face-to-face and online interviews from October to November 2023. After removing invalid responses (e.g., errors, duplicates, missing data), 34 valid datasets were obtained: 21 from experts and 13 from non-experts.

2.2.4 Q-Sorting

A normal-distribution scoring grid (Fig. 1) was provided for participants[38]. Scores ranged from −5 (least preferred) to +5 (most preferred), with 0 indicating neutral. Participants assigned image numbers into the grid according to their aesthetic preferences. Researchers explained the research objectives for participants to minimize biases from photographic techniques or image presentation. Participants were first asked to categorize images into three groups—liked (15 images), disliked (15 images), and neutral (6 images)—and then ranked them from "least preferred" to "most preferred" across all the grid cells; finally, participants were asked to provide brief explanations for their most and least preferred images for subsequent factor analysis.



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1. The normal-distribution scoring grid (adapted from Ref. [38]).

2.2.5 Factor Extraction and Interpretation

Firstly, the 34 sets of scoring results from were processed with PQMethod2.35, a statistical software, and parameters such as column range, depth of column, and sorts entered were set. Then, principal components factor analysis was used for data standardization, resulting in a table of factor eigenvalues. According to the Kaiser criterion, a total of 8 datasets with eigenvalues no less than 1 were selected[①][37]. Considering the principles of ensuring the structural clarity and variance explanation of factors and minimizing the number of factors[37][39], the research finally retained 5 datasets, i.e., the 5 major factors that visually impact the landscape by PV facilities in rural areas (Table 1). These 5 factors together explained 49% of the research variance, which met the requirements of this study. Finally, the varimax rotation of the factors was used to correspondingly calculate the factor loadings, which represent the correlation strengths between the samples and the factors; and the meanings of these 5 factors were interpreted as well.

The interpretation of the factors was mainly based on the semantic elaboration of each image, the image rankings, and the comments from the interview records, particularly through the semantic extraction of the reasons for the "least preferred" and

① Eigenvalue (EV) refers to the statistical strength and explanatory power of a factor. Factors of EV values no less than 1.00 were extracted for analysis in this study.

Table 1: Q-sorting and the factor loadings for P-samples

P-smaple	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
P1	0.1350	**0.6121X**	0.0364	0.2888	−0.1933
P2	0.4166	0.3892	−0.0835	−0.3505	0.4169
P3	**0.4703X**	0.2617	0.3407	0.1072	−0.1175
P4	0.1777	0.1371	0.1551	**−0.5547X**	0.0242
P5	0.2241	−0.0746	**0.6154X**	0.3340	0.2851
P6	0.2079	**0.7999X**	0.0631	0.2689	−0.0024
P7	**0.5363**	0.4079	−0.0468	0.2943	0.2715
P8	**0.4816**	**0.5926X**	−0.0168	0.1155	−0.1010
P9	**0.6440X**	0.2289	0.2575	−0.0040	0.0869
P10	0.3447	−0.0667	0.0938	0.0514	0.3388
P11	**0.4847**	0.0329	**0.5109X**	−0.0952	0.0961
P12	**0.7374X**	0.3713	0.1209	−0.0227	0.0664
P13	0.3065	0.5404X	0.2195	−0.1472	0.1745
P14	**0.4880**	−0.2662	0.3438	0.2764	−0.0164
P15	**0.5746**	0.1900	0.2866	**0.4468**	−0.1674
P16	0.3180	**0.7162X**	−0.1666	−0.0555	0.1821
P17	0.4036	0.3044	0.2251	−0.2568	0.2267
P18	**0.4737**	0.3193	0.1038	**0.4469**	0.2551
P19	0.0927	**0.5587X**	0.1247	−0.0660	−0.0671
P20	−0.0240	**0.6516X**	0.1672	0.2896	0.2606
P21	**0.5532X**	0.3498	0.2336	0.0218	0.0027
P22	0.1015	0.1955	**0.6592X**	−0.1582	0.2706
P23	**0.7346X**	−0.0452	0.0550	−0.2439	−0.0475
P24	0.2532	0.0503	**0.5619X**	−0.0768	−0.0415
P25	−0.0628	−0.2142	**0.5377X**	−0.3884	−0.0037
P26	−0.0406	0.0101	0.0755	0.0718	0.3227
P27	−0.0436	0.0827	0.3722	0.0663	**−0.5886X**
P28	0.0835	−0.1696	0.0524	−0.2941	−0.2468
P29	0.1049	0.2235	0.0101	**0.4848X**	−0.0863
P30	0.1176	0.1965	**0.6277X**	−0.1132	−0.0125
P31	**0.5498X**	0.2540	0.0995	0.2303	−0.1624
P32	**0.5481X**	0.3758	−0.0471	0.0099	0.1202
P33	0.0971	0.0504	−0.1603	**0.4617X**	0.1248
P34	0.0319	0.0642	0.2324	−0.0269	**0.4793X**
EV (%)	**15**	**13**	**9**	**7**	**5**

NOTE
Data indicated with "X" is a prompt from the PQMethod 2.35 analysis software that aligns with the factor loading formula. However, in fact, some information is missing, thus through manual calculation and verification, all the figures that are greater than or equal to 0.43 are bolded in the table.

"most preferred" choices. After qualitative analysis and researchers' interpretation, the meanings represented by each factor were summarized.

The factor loadings of P-sample on each factor must satisfy the formula:

$$|F| \geq 2.58 \times \frac{1}{\sqrt{n}} \text{ ,} \tag{1}$$

where F represents the loading of the factor in the P-sample, and n represents the number of P-sample. When the absolute value of F was greater than or equal to 0.43, the P-sample had significance on this factor (Table 1). Then participants with similar views were categorized to revealing the concerns of expert and non-expert groups to different factors (Table 2): The expert group paid more attention to Factors 4 and 5, while the non-expert group was more interested in Factor 2. Both groups showed less interest in Factor 3, while Factor 1 received common attention from the both groups.

3 Results

Through analysis and interpretation of each factor, the researchers defined the five factors as boundary integration,

Table 2: Factor classification attribution

Group	Factor					
	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	None
Expert	P8, P9, P11, P12, P14, P15, P18, P31, P32	P1, P13, P16	P11, P22	P4, P15, P18, P33	P27	P2, P10, P17, P26, P28
Non-expert	P3, P7, P21, P23	P6, P8, P19, P20	P5, P24, P25, P30	P29	P34	—
Total number	**13**	**7**	**6**	**5**	**2**	**5**

NOTES

1. The statistics are based on the experts, non-experts, and the factors corresponding to the bolded figures in Table 1. The number of significant factors associated with a P-sample may be one, multiple, or none.
2. "None" refers to the concerns of participants that were not included in these five factors.

morphological innovation, color richness and coordination, multifunction, and scale.

3.1 Factor 1: Boundary Integration

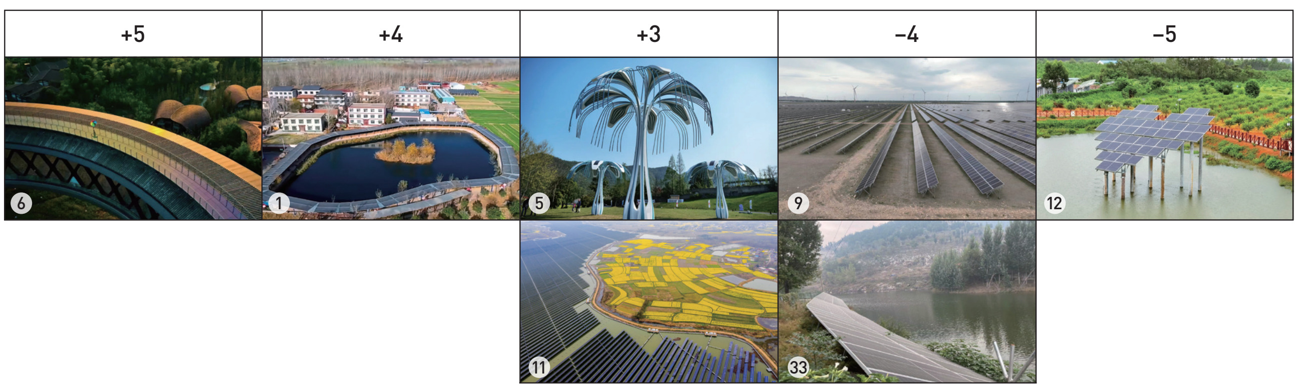
Nine experts and four non-experts showed significant correlations with this factor, making it the factor received the most attention of participants. It also has the strongest explanatory power, accounting for 15% of the variance explained. This factor reflects participants' emphasis on the harmonious coexistence of PV facilities with their surrounding environment, which can be enhanced through appropriate boundary design and adaptive arrangements. For example, Image 1 depicts a lakeside PV corridor in a village, where PV panels are arranged along the lakefront path, highlighting a dynamic aesthetic. Image 11 illustrates a rural fishery-PV project, where PV arrays are arranged in accordance with existing terrain variations, minimizing disruption to natural fabrics while optimizing land use efficiency. In contrast, PV facilities in Images 9, 12, and 33 exhibit rigid boundary design that lack harmonious integration with natural surroundings (Fig. 2).

3.2 Factor 2: Morphological Innovation

This factor accounted for 13% of the variance explained, ranking the second strongest explanatory power factor among the five. High-scoring images (e.g., Images 5, 6, 29) reveal that participants favored PV facilities with soft curvilinear forms, which combine functionality with artistic beauty. Conventional PV arrays that are often of monotonous designs (e.g., Images 9, 33) received lower scores due to their failure to meet contemporary aesthetic expectations. These findings suggest that innovative morphological designs can enhance public acceptance, with advancements in PV materials being critical to such innovations. As the emergence of thinner, flexible, transparent, or even bendable PV materials, PV facilities can better harmonize with rural natural landscapes through careful design (Fig. 3).

3.3 Factor 3: Color Richness and Coordination

Accounting for 9% of the variance explained, this factor reflects participants' preference for vibrant colors or environmentally harmonious color schemes of PV facilities. For instance, Image 25 (colorful PV facilities) and Image 6 (color-coordinated designs)



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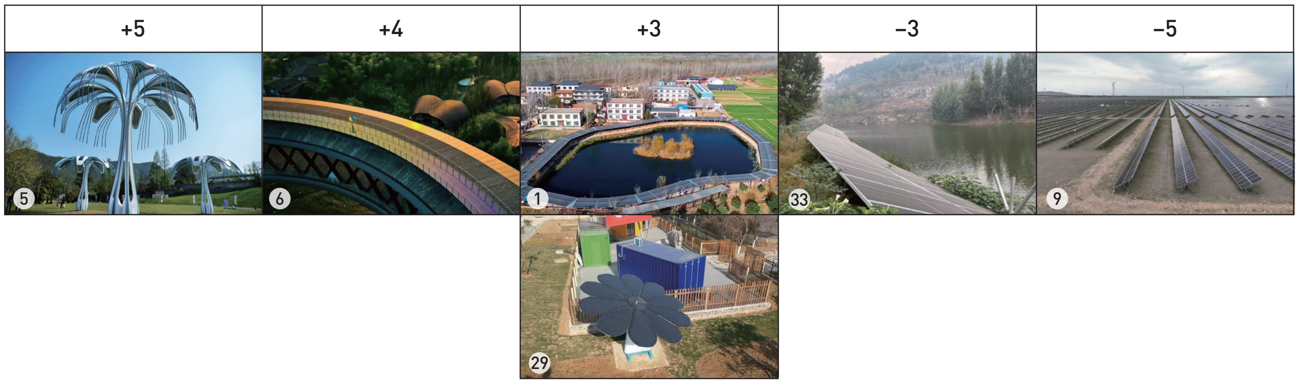
2. Sample images of boundary integration.



3. Sample images of morphological innovation.

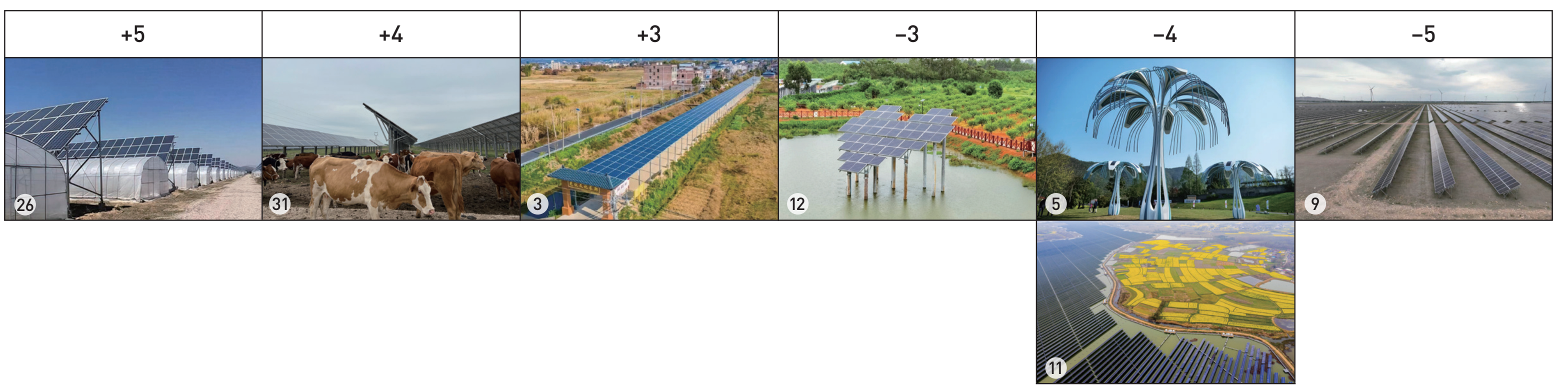
received high ratings. Image 6 features a cadmium telluride PV glass walkway in a mountainous rural area, where the color varies dynamically when the viewing angle changes. Conversely, PV materials dominated by black or dark blue hues (e.g., Images 1, 7) were less favored by participants. Designers and engineers are advancing color innovations of PV materials, creating visually appealing and effectively practical installations. Beyond thin-film PV materials, blue, green, and red cover glasses are now produced by crystalline silicon technologies with spectrally-selective reflection films[40]. Moreover, domestically-produced colored PV cells possess both efficient performance and attractive appearance[41], and colored semi-transparent cells surpass colorless ones in efficiency threshold[42] (Fig. 4).

3.4 Factor 4: Multifunction

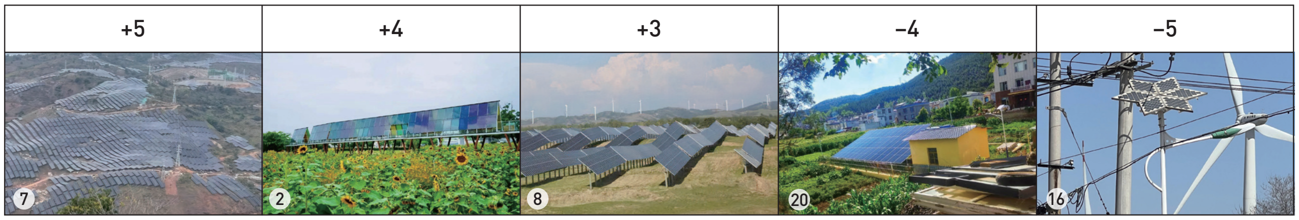
Accounting for 7% of the variance explained, this factor highlights participants' preference for multifunctional PV facilities. High-scoring examples (e.g., Images 3, 26, 31) integrate energy generation with land use efficiency, increasing the utilitarian value of space. In contrast, low-scoring facilities (e.g., Images 9, 33) often serve single purpose or neglect multifunctional potential. Future, PV facilities should emphasize comprehensive benefits (e.g., multifunctional PV plants[16]), contributing not only to energy transition but also to tourism, agriculture, and cultural initiatives (Fig. 5).

3.5 Factor 5: Scale

Accounting for 5% of the variance explained, this factor reflects participants' focus on PV facilities' scale in space or mass. As a low-density planar energy form, PV facilities require substantial land for ensuring energy output[43][44]. For instance, Image 7 displays a large-scale PV installation on rural highlands, where panels are arranged along the mountainous terrain to maximize solar absorption, enhancing the power generation efficiency. Lower-scoring cases are often smaller installations (e.g., Images 16, 20) and serve simply



4. Sample images of color richness and coordination.
5. Sample images of multifunction.



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6. Sample images of scale.

local energy needs[45]. Nevertheless, large-scale deployments may conflict with other land uses[46], necessitating systematic design and optimization schemes (Fig. 6).

3.6 Factor Correlation Analysis

Correlation analysis (Table 3) revealed the strongest positive correlation (0.5321) between Factor 1 (boundary integration) and Factor 2 (morphological innovation), with a large-percentage overlap of high-scoring images. These two factors also exhibited the strongest variance contributions, underscoring their centrality to PV facilities' visual impact on rural landscapes. Factors 1 and 2 represent two pathways to mitigate the visual degradation of rural natural landscapes caused by traditional linear PV layouts[10]. Factor 2 advocates reducing visual abruptness through innovative morphological design. As an alternative, Factor 1 emphasizes mitigation visual conflicts through boundary-blurring measures such as aligning PV layouts with natural contours and planting native vegetation to soften their edges[47]. Factors 3 and 4 showed the strongest negative correlation (−0.1598), which can be considered slightly correlated though, indicating that the negative correlation trends between the factors were not obvious.

4 Discussion

Based on the findings, this study discusses participants' visual satisfaction levels across three rural landscape types and then proposes strategies for PV facility planning and design.

4.1 Visual Satisfaction Levels Across Rural Landscape Types

Participants' visual satisfaction levels were analyzed by comparing the top 6 (considered "satisfied") and bottom 6 (considered "dissatisfied") images of each rural landscape type. Natural landscape images were scored "satisfied" 19 times and "dissatisfied" 14 times; settlement landscape images garnered "satisfied" only twice and "dissatisfied" 13 times; and production landscape images rated "satisfied" 9 times and "dissatisfied" 3 times.

Natural landscape images elicited the strongest polarized responses, suggesting that PV facilities in natural landscapes heightened strong emotional reactions and a significant disparity among the public. Notably, 53% of higher-rating images featured natural landscapes, suggesting they received a higher visual acceptance. However, natural landscapes also dominated the least preferred images. Participants disliked large standalone PV facilities (e.g., Images 8, 9) in natural landscapes, which disrupt ecological continuity and degrade natural aesthetics. Thus, introducing PV facilities into natural landscapes requires meticulous caution.

In terms of settlement landscape images, the frequency of satisfied images across various factors was the lowest, accounting for only 5% of the total, which was significantly less than the frequency of the dissatisfied ones. This reveals that such PV facilities ranked the lowest satisfaction among participants. By comparing the dissatisfied samples (e.g., Images 22, 23, and 24) with the satisfied ones (e.g., Image 15), it was found that the public reported a higher acceptance of PV facilities in rural settlement landscapes with aesthetic quality in design. However, most of the current PV facilities in rural settlement landscapes focus solely on their power generation by simply laying PV panels on rooftops or the ground, neglecting their aesthetic value, which led to negative evaluations from the participants.

For the images of PV facilities in production landscapes, the frequency of satisfied images across various factors was lower,

Table 3: Factor score correlations

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Factor 1	1.0000	**0.5321**	0.4022	−0.0135	0.0196
Factor 2	**0.5321**	1.0000	0.1628	0.1041	0.0076
Factor 3	0.4022	0.1628	1.0000	**−0.1598**	−0.0293
Factor 4	−0.0135	0.1041	**−0.1598**	1.0000	−0.1485
Factor 5	0.0196	0.0076	−0.0293	−0.1485	1.0000

accounting for 25% of the total, while that of the dissatisfied images was the lowest. This suggests that participants had a moderate satisfaction level about such PV facilities. Overall, the frequencies of both the satisfied and the dissatisfied were the lowest, indicating that when PV facilities are integrated into rural production spaces, their visual impacts on surrounding landscapes would be relatively low.

4.2 Planning and Design Strategies for Rural PV Facilities in Rural Landscapes

The planning and design for PV facilities in rural areas should prioritize ecological harmony and landscape integration[48][49], transforming PV systems into integral components of rural landscapes, beyond serving for energy generation demands. Integrating PV facilities into natural landscapes requires comprehensive assessments in ecology, aesthetics, and economy. Pre-planning steps—land use surveys, environmental assessments, and topographic mapping[50]~[52]—ensure that PV facilities harmonize with existing landscapes, balancing energy needs with ecological and social benefits.

In rural natural landscapes, the morphological innovation of PV facilities can be achieved by extracting regional cultural symbols to create PV facility forms that are harmonious with the surrounding environment. For instance, in Image 5, PV panels are designed as "leaves" of the local banyan trees, which softens the industrial image of traditional PV facilities and improves their visual harmony with the surrounding natural vegetation. In terms of color richness and coordination, it can be achieved by analyzing the color composition of the local natural landscapes and extracting the main and auxiliary color hues. For example, Image 2 features a colorful rainbow corridor built in a sunflower field, achieving a harmonious landscape of PV facilities with the natural environment. The boundary integration of PV facilities can be realized through layout designs that coordinate with natural topography, vegetation, and cultural landscapes, blurring the boundaries of PV facilities into the surrounding environment. For instance, Image 8 displays PV panels arranged along the natural contours of the site, not only making full use of the terrain but also minimizing the impact of artificial intervention on the natural landscape, and furthermore, creating a unique landscape rhythm that enhances visual harmony.

In settlement landscapes, PV facilities should emphasize multifunctional designs that provide clean energy generation while meeting the needs of rural living, cultural expression, and ecological conservation. Image 14 exemplifies this strategy by integrating PV panels onto the roof of an information board, combining solar energy generation while keeping the board's original function, thereby merging energy supply with public services. Such multifunctional designs would transform PV facilities into a critical part of rural energy systems by embedding them into public life as landscape nodes for energy generation and cultural and ecological purposes.

In production landscapes, where PV facilities exert minimal visual impacts, priority should be given to the increase of scale efficiency. Large-scale deployments in ecologically low-sensitivity areas or underused lands to optimize spatial resource utilization efficiency. Image 34 illustrates a salt-PV project where PV arrays are installed above salt pans, preserving salt production while efficiently harnessing solar energy.

5 Conclusions

This study systematically investigated the visual impact of PV facilities on rural landscapes using the visual Q-method and identified five factors: boundary integration, morphological innovation, color richness and coordination, multifunction, and scale. Analysis of the two participant groups revealed that non-experts paid more attention on color richness and coordination, whereas experts focused more on boundary integration and multifunction; and both groups emphasized morphological innovation. Correlation analysis indicated that the five factors are interconnected, with the factors of morphological innovation and boundary integration exhibiting the strongest positive correlations and the widest consensus among participants. The study further discussed the visual satisfaction levels across different rural landscape types and proposed planning and design strategies for PV facilities in rural areas.

Finally, this study has certain limitations. First, in the Q-sorting step, despite the participants were instructed to minimize biases from photographic techniques and image presentation of the Q-samples, their choices were inevitably influenced to some extent. Second, online and offline data collection approaches were employed in this study and the guidance for online participants was insufficient, leading to a higher proportion of invalid online responses during data screening. Therefore, offline questionnaires are recommended for future studies to ensure data quality and consistency.

ELECTRONIC SUPPLEMENTARY MATERIAL

Supplementary material is available in the online version of this article at https://doi.org/10.15302/J-LAF-1-020110.

Competing interests | The authors declare that they have no competing interests.

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基于视觉Q方法的光伏设施对乡村景观的视觉影响研究

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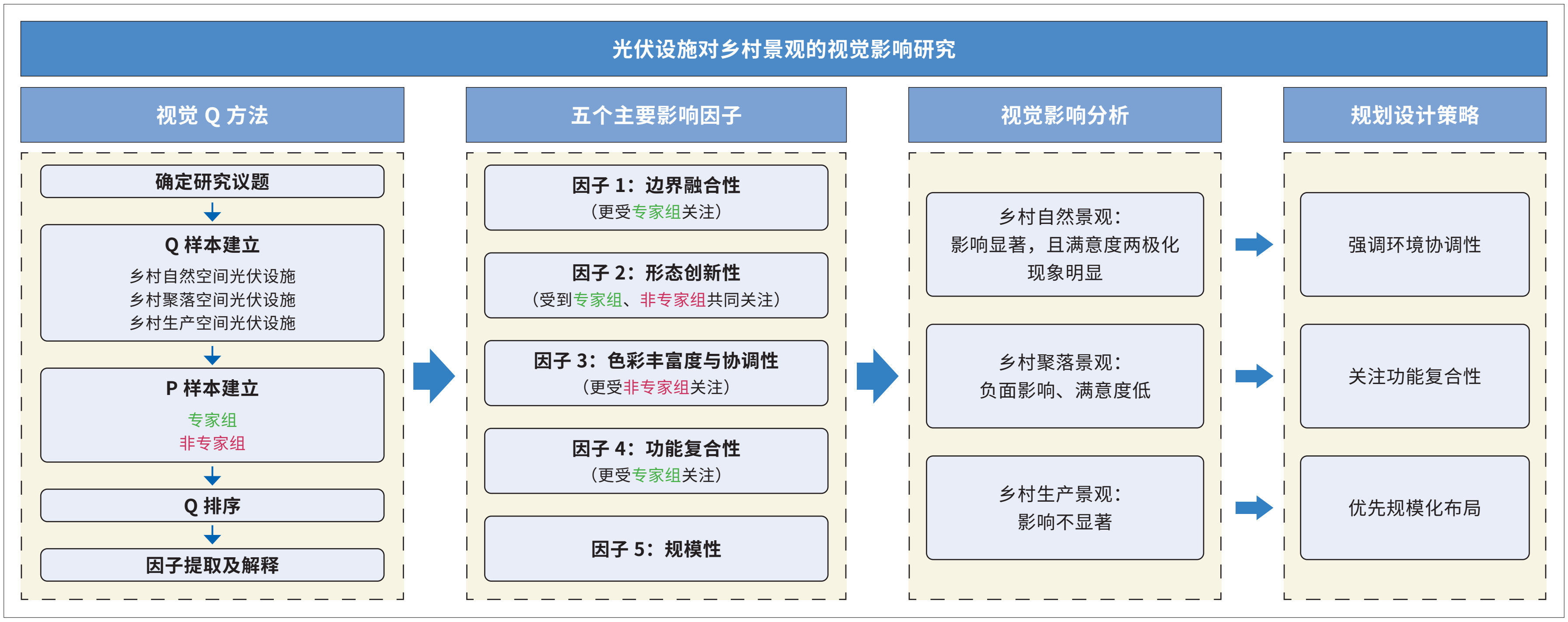
图文摘要



摘要

乡村地区充沛的空间资源使得光伏产业在乡村地区得到快速推进，大规模的光伏设施建设对乡村景观产生了显著影响。本研究采用视觉Q方法系统分析了光伏设施对乡村景观的视觉影响，通过选取中国不同地区的乡村自然景观、聚落景观和生产景观中的光伏设施图片，对专家组与非专家组两组受试者进行视觉评价调查，并使用PQMethod2.35软件对评分结果进行统计分析，从而得出光伏设施对乡村景观产生影响的5个主要因子：边界融合性、形态创新性、色彩丰富度与协调性、功能复合性和规模性。研究表明，光伏设施对乡村自然景观的视觉影响最显著，视觉满意度两极化现象明显；光伏设施对乡村聚落景观有负面影响，不满意频次显著高于满意频次；光伏设施对乡村生产景观的视觉影响不显著。研究结果有助于为乡村地区光伏景观规划设计提供参考，助力乡村地区光伏设施的可持续建设与发展。

关键词

视觉Q方法；乡村景观；光伏设施；光伏景观；视觉影响

文章亮点

- 研究发现边界融合性、形态创新性、色彩丰富度与协调性、功能复合性和规模性5个主要影响因子
- 光伏设施对乡村自然景观视觉影响显著，但视觉满意度存在明显分歧，实践中应注重边界融合性
- 光伏设施对乡村聚落景观有负面影响，实践中应关注功能复合性
- 光伏设施对乡村生产空间视觉影响不显著，实践中可优先考虑规模化布局

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编辑 田乐，汪默英

1 引言

气候变化问题日益严峻，国际社会对减少温室气体排放、缓解气候变化的紧迫性达成了广泛共识，减少化石能源的使用、加快向清洁能源转型已成为全球能源发展的必然趋势[1]。光伏发电系统作为高效可行的太阳能利用途径[2]，近年来在各国能源政策的引领下，其应用得到了迅猛发展[3]。根据欧盟委员会的数据，2010~2023年，全球光伏装机容量1 608GWp，中国累计装机容量约为671GWp，约占全球总装机容量的42%[4]。随着乡村经济的发展和生活水平的提高，乡村地区将成为中国未来新增电力的主要来源和电力需求的主要地区。调查表明，中国农村屋顶光伏可安装规模总量为19.7亿千瓦，开发潜力巨大[5]。同时，光伏产业在乡村地区衍生出的各种“光伏+”模式，如农光互补、渔光互补、牧光互补、林光互补等，大大提高了乡村资源的综合利用率[6][7]。

与城市相比，乡村通常拥有更接近自然的生态环境，也更易受到光伏设施建设的潜在影响。尽管与传统化石能源相比，光伏能源在环境效益上具有显著优势，但大规模的光伏设施建设也会带来包括大量土地占用、乡村景观或局部生态环境变化等影响，这些问题也逐渐引起了社会的广泛关注[8]。荷兰[8]、加拿大[9]等国家和地区推广了大规模可再生能源设施的建设，但其所造成的视觉冲击引发了公众的强烈反对。基于这一背景，许多学者提出了若干大型新能源设施的视觉影响评估方法[10]~[12]，并将大型风电设施的视觉影响评估方法逐渐运用到大型地面光伏设施上[13]。研究者们基于可见性、颜色、分形度和并发性提出了视觉影响的量化指标及计算方法。例如，基亚白兰度·罗伯托等人使用视觉影响评估工具OAI_{SPP}评估了光伏电站对景观的视觉影响[14]。

在早期的光伏设施视觉评价研究中，大多数研究者往往基于其视觉影响总是负面的且必须被消减、光伏发电系统必须被隐藏的研究语境，较少讨论如何将光伏发电系统与景观环境进行积极融合。2016年，亚历山德拉·斯科尼亚米利奥等人通过包容性设计方法提出“光伏景观”理念[2]，将光伏发电系统作为景观设计的一部分，从而降低光伏发电系统的视觉影响。迪克·奥德斯等人在2021年提出将太阳能发电厂和景观结合起来进行空间布置的“太阳能景观”[15]；2022年，又建立了“太阳能能源景观”的概念框架，涵盖可持续技术、经济、环境和社会等方面[16]。

2003年，中国学者开始论及光伏发电系统与景观环境的结合[17]，研究多以推动光伏发电系统建设为目的，议题包括景观要素与光伏设施相结合的设计[18]、数字化光伏技术在乡村景观设施中的应用[19]、光伏小镇规划及发展模式[20]、光伏生态休闲农业园建设模式[21]等。目前国家政策对光伏发电系统的选址已有明确规定，要求避让耕地、生态保护红线、历史文化保护线、天然林地、水体等[22][23]，但针对光伏设施建设对乡村地区景观的视觉影响尚缺乏系统性研究，相关管控细则尚未完善，导致在实际规划建设中缺乏具体的景观协调性指导标准。这使得乡村地区在推进光伏项目时难以有效平衡可再生能源发展与景观保护之间的关系，亟须科学评估光伏设施对乡村景观产生的视觉影响，为政策制定提供依据。

视觉Q方法作为一种结合主观感知与定量分析的研究方法，在景观评价与规划领域具有高效、直观的优势。该方法最早由欧文·H. 祖贝等人应用于景观评价和规划[24]，继而又应用于不同研究场景。例如，西蒙·斯沃菲尔德和约翰·R. 费尔韦瑟通过视觉Q方法以不同的景观照片来调查游客对新西兰用地变化的态度[25]，也通过视觉Q方法和景观照片探讨了游客的体验差异[26]，展示了该方法在旅游体验研究中的有效性；安德拉·约安娜·米尔库等人基于视觉Q方法，探讨了罗马尼亚乡村居民对景观的多样化偏好和潜在冲突[27]。在光伏设施建设引发的视觉影响研究方面，西蒙娜·南纳斯佩蒂等人通过收集意大利城市和农村环境中各种

光伏电站的景观图像，使用视觉Q方法探索了光伏电站对当地景观与土地利用的影响[24]；陆明等人采用Q方法探索了不同城市土地利用类型中光伏发电系统对城市景观的影响[28]。基于上述研究，本研究旨在采用视觉Q方法，系统评估光伏设施对中国乡村景观的视觉影响，为中国乡村地区光伏设施建设的可持续发展提供科学依据。

2 研究方法与数据采集

2.1 Q方法概述

英国心理学家威廉・斯蒂芬森于20世纪30年代首次提出“Q方法”（Q-Methodology），并在1952年发表的《Q方法与投影技术》[29]中进行了详细论述。Q方法是一种定量和定性相结合的研究方法。与运用大量随机数据为样本的传统统计方法不同的是，Q方法是一种小样本量的研究方法，强调针对少量受试者进行大量测试，或者从受试者中寻找大量回馈[30]。20世纪80年代以来，Q方法研究逐渐从心理学领域拓展到健康科学、护理学、政策科学、公共行政、环境经济学等学科领域[30]。

Q方法的研究一般包括5个步骤[31]。1）确定研究议题；2）确定Q样本：Q样本需要尽可能涵盖研究议题的所有可能性观点；3）确定P样本（即受试者）：在受试者的选择上，只要研究者认为该受试者能够针对研究议题提供有趣或重要的观点即可，并根据研究需求确定受试者组成及数量；4）Q排序（Q-Sorting）：辅助受试者知悉研究目的，并完成Q样本的排序；5）因子提取及解释：将受试者打分结果输入软件进行统计分析，确定出最终的研究结果并对其进行分析及解释。

Q方法可作为连接人类感知与环境的一种手段[28]。需要说明的是，在Q方法样本建立的过程中，Q样本不仅可以是语言文字，也可以是绘画、艺术品、图片、音乐作品、视频等表达形式的集合[32]。就目前的研究而言，国内外将语言文字作为Q语句集的形式更加常见，但其他的表达形式也各有优势。例如，以视觉形象作为Q样本进行测试的方法被称为“视觉Q方法”[33]。当图像作为Q样本时，可以给受试者带来更加直观、真实的场景体验，受试者还可以凭借图片回忆起关于类似场景的无法用语言传达的情感、记忆和思想，使得受试者的访谈更加有效可靠。

2.2 研究设计

2.2.1 确定研究议题

根据研究目的，本研究议题确定为运用视觉Q方法探究光伏设施对乡村景观的视觉影响。

2.2.2 确定Q样本

本研究将能够反映乡村地区光伏设施及其周边环境关系的照片作为Q样本，遴选主要关注乡村景观形态类型[34]和光伏组件的应用形式[24]两个方面。乡村景观形态可分为乡村自然景观、乡村聚落景观和乡村生产景观三类[34]。乡村自然景观包括乡村空间中的河流、植物、山地、自然保护区等；乡村聚落景观指与人的生活环境密切相关的建筑空间；乡村生产景观指的是乡村的生产劳动和劳动成果融为一体的景观类型，包括农业景观、林业景观、畜牧业景观等[34][35]。光伏组件的应用形式大体上可分为一体化形式和非一体化形式[24]。在乡村地区中，一体化光伏组件的应用形式大多通过单体附加或饰面材料的形式与乡村设施或构筑物进行结合；非一体化光伏组件的应用形式大多以光伏板或单体光伏雕塑等形式出现[36]。研究广泛收集了中国各地乡村景观中包含光伏设施的图片，并对图片进行筛选（包括剔除特征相似、无代表性的图片[24]），最终遴选出36张图片作为Q样本，包含6个类别：乡村自然景观中的一体化光伏设施（1～6号图片）、乡村自然景观中的非一体化光伏设施（7～12号图片）、乡村聚落景观中的一体化光伏设施（13～18号图片）、乡村聚落景观中的非一体化光伏设施（19～24号图片）、乡村生产景观中的一体化光伏设施（25～30号图片），以及乡村生产景观中的非一体化光伏设施（31～36号图片）。

2.2.3 确定P样本

为了体现P样本所代表观点的多样性，研究将受试人群分为两类：对光伏设施及乡村景观有所了解的“专家”和了解不多的“非专家”。专家组包括景观设计师、建筑师、规划师和光伏工程师，非专家组包括村民、乡村旅游者及对此研究感兴趣的其他人群。

在P样本的人数选取上，Q方法并没有对P样本的数量做出明确的要求，一般来说应少于Q样本数量[37]。但考虑到后期可能会存在部分无效数据，故本研究前期酌情增加了P样本的数量。鉴于专家更有可能参与影响乡村光伏设施建设政策的制定及实施过程[24]，因此本研究中专家组人数略多于非专家组——专家组24人，非专家组17人。研究团队于2023年10～11月通过面对面访谈与在线访谈两种方式收集两组受试者的评价数据。在筛除理解错误、数据重复、数据缺失等无效数据后，研究团队共征集到34份受试者的有效数据，其中专家组有效数据有21份，非专家组有效数据有13份。

2.2.4 Q排序

研究团队准备了供受试者打分的正态分布表格[38]（图1），分值范围为-5～5，-5代表最不喜欢，5代表最喜欢，0代表无偏好。受试者需根据个人对图片的审美偏好，在分值表格内填写对应的图片编号。研究者向受试者解释了本研究的目的与注意事项，需要受试者尽量克服由于拍摄技巧及图片表现所带来的干扰。在具体的打分过程中，首先要求受试者将图片分成三组：喜欢的15张，不喜欢的15张，无偏好的6张；然后，要求受试者将图片放入36个空格中，从“最不喜欢”到“最喜欢”进行排

列；最后，将图片编号填入表格中，并要求受试者简要阐述最喜欢和最不喜欢图片的理由，以期为后续影响因子的分析及讨论提供参考。

2.2.5 因子提取及解释

首先，将34份受试者打分结果输入统计软件PQMethod2.35中，并完成列范围、列深度、待输入样本数量等参数设定；然后，使用主成分分析法对数据进行标准化处理，得到因子的特征值表。依据Kaiser法则，选取出特征值大于等于1[①]的影响因子数据集[37]共计8组；再依据因子需具有一定的结构清晰度和方差解释度、尽可能少地保留影响因子数量等原则[37][39]，最终保留了5组影响因子数据集，即本研究中乡村地区光伏设施对景观的视觉影响的5个因子（表1）。这5个因子共解释了49%的研究方差，满足本研究要求。最后，研究采用方差极大旋转法对这5个因子进行旋转，并计算其因子载荷，即样本和因子的相关强度，并对这5个因子分别进行含义解释。

因子的解释主要依据每张图片的语义阐述和图片排名，以及访谈记录的受试者评论，特别是对受试者“最不喜欢”和“最喜欢”理由的语

① 特征值表示一个因子的统计强度和解释力，当 EV 的值为 1.00 时，通常将 1.00 作为因子提取和保留的临界点，所以本研究保留 EV 值不小于 1.00 的因子进行分析。

表 1：P 样本及其因子载荷

P 样本	因子 1	因子 2	因子 3	因子 4	因子 5
P1	0.1350	**0.6121X**	0.0364	0.2888	−0.1933
P2	0.4166	0.3892	−0.0835	−0.3505	0.4169
P3	**0.4703X**	0.2617	0.3407	0.1072	−0.1175
P4	0.1777	0.1371	0.1551	**−0.5547X**	0.0242
P5	0.2241	−0.0746	**0.6154X**	0.3340	0.2851
P6	0.2079	**0.7999X**	0.0631	0.2689	−0.0024
P7	**0.5363**	0.4079	−0.0468	0.2943	0.2715
P8	**0.4816**	**0.5926X**	−0.0168	0.1155	−0.1010
P9	**0.6440X**	0.2289	0.2575	−0.0040	0.0869
P10	0.3447	−0.0667	0.0938	0.0514	0.3388
P11	**0.4847**	0.0329	**0.5109X**	−0.0952	0.0961
P12	**0.7374X**	0.3713	0.1209	−0.0227	0.0664
P13	0.3065	0.5404X	0.2195	−0.1472	0.1745
P14	**0.4880**	−0.2662	0.3438	0.2764	−0.0164
P15	**0.5746**	0.1900	0.2866	**0.4468**	−0.1674
P16	0.3180	**0.7162X**	−0.1666	−0.0555	0.1821
P17	0.4036	0.3044	0.2251	−0.2568	0.2267
P18	**0.4737**	0.3193	0.1038	**0.4469**	0.2551
P19	0.0927	**0.5587X**	0.1247	−0.0660	−0.0671
P20	−0.0240	**0.6516X**	0.1672	0.2896	0.2606
P21	**0.5532X**	0.3498	0.2336	0.0218	0.0027
P22	0.1015	0.1955	**0.6592X**	−0.1582	0.2706
P23	**0.7346X**	−0.0452	0.0550	−0.2439	−0.0475
P24	0.2532	0.0503	**0.5619X**	−0.0768	−0.0415
P25	−0.0628	−0.2142	**0.5377X**	−0.3884	−0.0037
P26	−0.0406	0.0101	0.0755	0.0718	0.3227
P27	−0.0436	0.0827	0.3722	0.0663	**−0.5886X**
P28	0.0835	−0.1696	0.0524	−0.2941	−0.2468
P29	0.1049	0.2235	0.0101	**0.4848X**	−0.0863
P30	0.1176	0.1965	**0.6277X**	−0.1132	−0.0125
P31	**0.5498X**	0.2540	0.0995	0.2303	−0.1624
P32	**0.5481X**	0.3758	−0.0471	0.0099	0.1202
P33	0.0971	0.0504	−0.1603	**0.4617X**	0.1248
P34	0.0319	0.0642	0.2324	−0.0269	**0.4793X**
EV (%)	**15**	**13**	**9**	**7**	**5**

注
带 X 的数据是 PQMethod2.35 分析软件自带的符合因子载荷公式的提示，但是实际上有所遗漏。因此，通过公式手动计算和确认出大于等于 0.43 的数值，并全部加粗。

义提取。在对每个因子进行定性分析和主观解释后，最终总结归纳出每个因子所代表的含义。

P样本在各因子上的因子载荷需满足如下公式：

$$|F| \geq 2.58 \times \frac{1}{\sqrt{n}}, \quad (1)$$

其中，F表示因子在某P样本中的载荷，n表示P样本数量。F绝对值大于等于0.43时，此P样本在该因子上具有显著性（表1）。通过对观点相似的受试者进行归类，可以发现专家组和非专家组对不同因子的关注程度（表2）：专家组对因子4和因子5关注相对较多，非专家组对因子2更感兴趣，两组对因子3都关注较少，而因子1得到了两组的共同关注。

3 研究结果

经过对每个因子的分析和解释后，研究者将5个因子所代表的含义分别总结归纳为：边界融合性、形态创新性、色彩丰富度与协调性、功能复合性和规模性。

3.1 因子1：边界融合性

分别有9名专家和4名非专家与该因子显著相关，是受关注最多的影响因子。该因子的方差贡献率为15%，也是解释力最强的因子。本因子体现出受试者对于光伏设施与所处环境的和谐共存的关注，即使光伏设施可以通过适宜的边界处理和不同的排列方式，与自然环境更加融合呼应。例如，1号图片是位于村庄内的环湖光伏长廊，设计师依据环湖路径来排列光伏板，使得光伏长廊更具动态感和流动美；11号图片是乡村的渔光互补项目，其中光伏板的阵列排布依据地形变化错落布置，在有效利用空间的同时减少了对自然肌理的破坏，呈现出顺应环境自然边界的姿态。相反，9、12、33号图片中的光伏设施的边界处理在视觉上显得较为生硬，缺乏与自然环境的融合（图2）。

3.2 因子2：形态创新性

该因子的方差贡献率为13%，在五个因子中解释力排名第二。从得分较高的图片（如5、6、29号）可以看出，设计师充分呈现了光伏设施柔和的曲线形态，创造出既实用又具有艺术美感的景观，获得了受试者的喜爱。而常规的光伏阵列在外观形态上表现得较为单一枯燥，难以满足当代社会的审美需求，在该组中普遍得分较低（如9、33号）。这一研究结果说明，将光伏组件组合成更具创新性的形态更容易得到公众认可，而光伏材料的创新是推动光伏景观形态革新的关键。随着更加轻薄、灵活、透明，甚至可弯曲的光伏材料的问世，光伏设施可以更好地融入乡村的自然景观环境中（图3）。

3.3 因子3：色彩丰富度与协调性

该因子的方差贡献率为9%。本因子表现出受试者对光伏设施颜色丰富度及色彩搭配的偏好：他们更加喜欢色彩鲜艳的光伏设施（如25号），或者光伏设施的颜色与周围环境颜色相协调的图片。例如，6号图片是位于乡村山野间的彩色碲化镉光伏玻璃栈道，随着观看角度的变化，光伏玻璃栈道的颜色呈现出绚丽多彩的渐变效果。相反，以黑色和深蓝色为主的光伏设施（如1、7号）并没有得到受试者的喜爱。在光伏材料的色彩创新方面，设计师和工程师们正致力于打破传统观念，将光伏板的功能性与艺术性更好地融合，创造出既实用又具有视觉吸引力的

表 2：因子分类归属表

类别	影响因子					
	因子 1	因子 2	因子 3	因子 4	因子 5	无
专家组	P8、P9、P11、P12、P14、P15、P18、P31、P32	P1、P13、P16	P11、P22	P4、P15、P18、P33	P27	P2、P10、P17、P26、P28
非专家组	P3、P7、P21、P23	P6、P8、P19、P20	P5、P24、P25、P30	P29	P34	—
总计（个）	**13**	**7**	**6**	**5**	**2**	**5**

注

1. 依据表 1 中加粗数值所对应的受试者专家、非专家身份和因子进行分组统计。一个受试者对应的显著性因子数量可能是一个、多个，或没有。
2. “无”是指受试者所关注的因素不在此 5 个因子当中。

新型景观。当前，除薄膜光伏材料外，晶硅光伏技术也利用光谱选择性反射膜研发出了蓝色、绿色、红色等颜色的盖板玻璃[40]。此外，在能源转化效率上，中国彩色光伏电池早已具备“高效”和“美观”双重特点[41]，并且彩色的半透明光伏电池的极限效率已超过无色的半透明光伏电池[42]（图4）。

3.4 因子4：功能复合性

该因子的方差贡献率为7%。本因子表现出受试者对光伏设施功能复合性的偏好。除了基本的能源生产，得分较高的光伏设施（如3、26、31号）都实现了土地资源的高效利用，拓展了空间的使用价值。与之形成对比的是，9、33号等得分较低的光伏设施的功能相对单一，仅满足了基本的发电需求，未能充分挖掘光伏设施在功能复合性方面的潜力。未来，光伏设施为公众带来的综合利用效益（如多功能的复合型光伏电站[16]）将愈发凸显，不仅能为能源结构的转型做出贡献，而且在观光旅游、农牧业生产、文化教育等领域都将发挥积极作用（图5）。

3.5 因子5：规模性

该因子的方差贡献率为5%。本因子表现出受试者对光伏设施空间规模的关注。作为一种低密度的平面能源形式，光伏发电设施需要足够的空间[43][44]，光伏设施的项目规模越大，需要的土地越多，从而获得足够的发电效益。例如，7号图片是位于乡村高山上的光伏设施，在合理利用高山闲置资源的基础上，依据山体起伏走势进行大面积的光伏板铺设，满足了最大规模的太阳能辐射吸收，提升了发电效益。相反，得分较低的光伏设施（如16、20号）规模较小，只满足了自身或较小范围的用电需求[45]。值得注意的是，大面积的光伏板铺设可能会引起与其他土地利用形式之间的资源矛盾[46]，需要综合考量各因素进行系统设计和优化（图6）。

3.6 因子相关性分析

各因子相关性分析结果显示（表3），因子1（边界融合性）和因子2（形态创新性）之间呈现出最强的正相关性（0.5321），联系也最为密切（两个因子中得分较高图片重合度极高）。同时，因子1和因子2的方差贡献率最大，解释力度最强，说明这两个因子是光伏设施对中国乡村景观产生视觉影响的核心因素。通常情况下，光伏设施以直线排布形式介入乡村环境中，打破了乡村环境原有的自然形态[10]，因子1和因子2可视为针对这一问题的不同解决方案。因子2强调对光伏设施的外观形态进行创新，减少光伏设施引入乡村空间时的突兀感。相较而言，因子1侧重于通过顺应光伏设施周边环境的边界形态、在光伏设施周边种植与乡村环境匹配的植物等方式[47]模糊光伏设施与乡村环境的边界，从而减少视觉冲突。另一方面，因子3和因子4具有最强负相关性，但数值仅为–0.1598，说明本研究的5个因子两两之间没有明显的负相关趋势。

表 3：因子得分相关性

	因子 1	因子 2	因子 3	因子 4	因子 5
因子 1	1.0000	**0.5321**	0.4022	– 0.0135	0.0196
因子 2	**0.5321**	1.0000	0.1628	0.1041	0.0076
因子 3	0.4022	0.1628	1.0000	**– 0.1598**	– 0.0293
因子 4	– 0.0135	0.1041	**– 0.1598**	1.0000	– 0.1485
因子 5	0.0196	0.0076	– 0.0293	– 0.1485	1.0000

4 讨论

基于以上分析结果，本研究将从受试者对乡村不同空间类型中光伏设施的视觉满意度和光伏设施规划设计策略两个方面进行讨论。

4.1 不同乡村空间类型中光伏设施的视觉满意度

研究选取乡村不同空间类型下各因子排名前6位（较为满意）和后6位（较不满意）的图片，统计分析光伏设施引入不同空间类型中的视觉满意度。结果显示，乡村自然景观中的光伏设施图片共被评为较为满意19次，较不满意14次；乡村聚落景观中的光伏设施图片仅2次被评为较为满意，13次被评为较不满意；乡村生产景观中的光伏设施图片共9次被评为较为满意，3次被评为较不满意。

乡村自然景观中的光伏设施在各因子下被评为较为满意和较不满意的频次均最多，这表明乡村自然景观中的光伏设施会引发受试者较为强烈的情绪反应，且公众意见的分歧较大。在较为满意的图片中，乡村自然景观中的光伏设施占比为53%，表明在乡村各类景观空间中，公众对乡村自然景观中光伏设施的视觉满意度最高。同时，在较不满意的图片中，乡村自然景观中的光伏设施图片出现频次也最多。大多数受试者不喜欢大规模安装在乡村自然景观中的非一体化光伏设施（如8、9号），这些设施往往破坏了乡村自然景观的连续性和整体性，且光伏设施“冰冷”的外观形态也与自然环境显得格格不入。因此，在乡村自然景观中引入光伏设施要保持高度谨慎。

在乡村聚落景观中的光伏设施图片中，各因子下被评为较为满意的频次最少，仅占总数的5%，且显著低于较不满意的频次，表明受试者对乡村聚落景观中引入光伏设施的视觉满意度最低。通过对比较不满意图

片（如22～24号）和较为满意图片（如15号）发现，公众对乡村聚落景观中具有造型美感的光伏设施评价较高，而目前多数乡村聚落景观中的光伏设施建设仅注重其发电功能，只是将一些光伏板简单地铺设在屋顶或地面上，忽视其视觉形象的美感，因此受试者给予了负面评价。

在乡村生产景观中的光伏设施图片中，各因子下被评为较为满意的频次较少，占总数的25%，但较不满意的频次最少。表明受试者对乡村生产空间中的光伏设施视觉满意度适中。整体而言，较为满意和较不满意图片的频次整体最少，表明当光伏设施结合乡村生产空间进行布置时，其产生的视觉冲击相对较低。

4.2 乡村地区光伏设施景观规划设计策略

在乡村地区进行光伏设施规划设计时，应遵循生态优先、景观协调的原则[48][49]，使光伏设施不仅可以作为乡村能源的提供者，更应成为乡村景观的重要组成部分。光伏设施融入乡村自然景观时需要综合考量生态、景观、经济等多方面因素，在规划设计前期，深入开展土地利用调查、自然条件勘察、地形地貌测绘[50]~[52]，同时对乡村景观视觉影响进行评价与论证，通过科学合理的规划设计，使光伏设施不仅满足能源供给需求，还可以与乡村既有景观有机融合，降低视觉突兀感，实现生态环境、社会满意度与经济效益的多赢。

在乡村自然景观中，光伏设施的形态创新可通过提炼地域文化符号，创造出与周边环境相协调的光伏设施形态来实现。例如，5号图片中，结合当地榕树的形态，将光伏板巧妙地嵌入“叶片”之中，弱化了传统光伏设施的工业感，与周围的自然植被形成协调统一的视觉效果。色彩的丰富度与协调性方面可以通过深入分析自然空间中景观的色彩构成，提取其主色调与辅助色调来实现。例如，2号图片中，色彩丰富的彩虹廊桥点缀在向日葵花海中，实现光伏设施与自然环境的和谐共存。光伏设施的边界融合性方面可以通过设计与自然地形、植被及人文景观相协调的光伏设施布局来与周边环境柔和衔接。例如，8号图片中，光伏板沿着地形的自然起伏轮廓排列，既充分利用了地形特点，又减少了人工干预对自然地貌的破坏，还形成了独特的景观韵律感，增强了视觉上的和谐性。

在乡村聚落景观中，应尽量强化光伏设施的功能复合性，通过多功能集成设计，在提供清洁能源的同时，满足乡村生活、文化展示及生态保护等多重需求。例如，14号图片中，将光伏板与宣传栏顶部结合，既充分利用宣传栏的顶部空间实现太阳能发电，又保留了宣传栏原有的信息传播功能，实现了能源供给与公共服务的有机结合。通过这种功能复合性设计，光伏设施不仅成为乡村能源系统的重要组成部分，还融入了乡村公共生活，成为兼具生产性、文化性与生态性的多功能景观节点。

在乡村生产景观中，光伏设施产生的视觉影响较低，可优先考虑提高光伏设施的规模效益，优先选择土地利用率低、生态敏感性较低的区域进行规模化开发，提高空间资源综合利用效率。例如，34号图片中，采用“盐光互补”模式，在盐田上方架设光伏板阵列，既保留了盐业生产功能，又实现了清洁能源的高效利用。

5 结语

本研究采用视觉Q方法研究了光伏设施对乡村景观的视觉影响，并提炼总结出5个主要影响因子：边界融合性、形态创新性、色彩丰富度与协调性、功能复合性和规模性。通过对两组受试者的试验结果的分析发现，非专家组对光伏设施的色彩丰富度与协调性关注更高，而专家组则对光伏设施的边界融合性、功能复合性两个方面更加感兴趣；形态创新性受到了两组受试者的共同关注。相关性分析结果显示，5个因子并不是孤立存在的，形态创新性和边界融合性两个因子之间的关联最为密切，受试者对二者的共识度也最高。此外，研究还讨论了光伏设施引入乡村不同空间的视觉满意度，以及乡村景观中光伏设施的规划设计策略。

最后，本研究也存在一定的不足之处。首先，在Q排序过程中，尽管研究团队向受试者强调尽量不要被Q样本的拍照技巧和图片表现等因素所影响，但显然这些因素仍会在一定程度上干扰受试者的选择。其次，在受试者填写问卷的过程中，本研究采取的是线上和线下结合的形式，线上给予的指导没有线下充分，在后期筛选问卷的过程中，无效的线上问卷相对较多。因此，后续研究中应尽量选择线下问卷的形式来保证调研结果的效率和质量。

补充材料

可通过https://doi.org/10.15302/J-LAF-1-020110查看本文补充材料。

图 1. 受试者打分正态分布表格（改绘自参考文献 [38]）
图 2. 边界融合性相关图片示例
图 3. 形态创新性相关图片示例
图 4. 色彩丰富度与协调性相关图片示例
图 5. 功能复合性相关图片示例
图 6. 规模性相关图片示例